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90.2011

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By **Ardjan Gazheli**, Department of Economics, SLU

Luca Di Corato, Department of Economics, SLU

Climate Change and Sustainable Development Series
Editor: Carlo Carraro

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Keywords: Land Allocation, Real Options, Renewable Energy, Solar farm, Uncertainty

JEL Classification: C61, D81, Q24, Q42

We wish to thank Jeroen van den Bergh, William Redekop, Chelsey Jo Huisman and Tinoush Jamali Jaghdani for helpful comments. The usual disclaimer applies.

Address for correspondence:

Ardjan Gazheli
Department of Economics, SLU
Box 7013, Johan Brauners väg 3
Uppsala 75007
Sweden
Phone: +46(0)706065299
Fax: +46(0)18673502
E-mail: a.gazheli@gmail.com

Land-use change and solar energy production: a real option approach*

Ardjan Gazheli† Luca Di Corato‡

November 3, 2011

Abstract

In this paper a real option model is developed to examine the critical factors affecting the decision to lease agricultural land to a company installing a PV power plant. The leasing payment is certain while the net revenues from agriculture are uncertain. We identify the profit values at which the farmer decides to lease his plot vs. continue farming it. By applying the model to the province of Bologna (Italy), we illustrate the possible land-use change scenarios in this area. We conclude by discussing the importance of PV energy production as a source of income for farmers and its implications from a social perspective.

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[†] Corresponding author: Department of Economics, SLU, Box 7013, Johan Brauners väg 3, Uppsala, 75007, Sweden. Email: a.gazheli@gmail.com. Telephone: +46(0)706065299. Fax: +46(0)18673502.

[‡] Department of Economics, SLU, Box 7013, Johan Brauners väg 3, Uppsala, 75007, Sweden. Email: luca.di.corato@slu.se. Telephone: +46(0)18671758. Fax: +46(0)18673502.

1 Introduction

The rising demand for electricity and concern over the environmental impact of using fossil fuels for its production have driven increasing consideration for investment in renewable energy sources (World Wildlife Fund 2011). Among them, sunlight, convertible into electricity using photovoltaic (PV) technology, represents an option capable of meeting both concerns since it is an abundant and unlimited source of clean energy.[1]

Despite the delay with respect to some European countries such as Germany and Spain, the PV industry has started growing significantly in Italy. In the last few years, the number of power plants have grown from 7,647 installations with a PV power potential of 87 MW in 2007 to 155,977 installations with a 3,469.9 MW power potential at the end of 2010 (GSE[2] 2011a; GSE 2011b). Apart from the favourable conditions resulting from its geographical position, incentives introduced by the government have played a crucial role in this trend of continuous development. In particular, investments in the sector has benefited from the feed-in tariffs, the so called "*Conto Energia*", introduced by decree n. 387 on December 2003, which implements the European Directive 2001/77/EC (Presidenza della Repubblica 2011; EC 2001). Since the decree came into effect in 2006, operators investing in PV energy production have benefited from an advantageous feed-in premium scheme, that pays a bonus on top of the market electricity price for a period of 20 years (Ministero dello Sviluppo Economico 2011).

Several types of PV power plants may qualify for a grant under the scheme. In general, the installations are divided into rooftop and ground-based. The first category is installed on buildings such as homes, shopping malls and industrial sheds and is common in urban and industrial areas. On the contrary, ground-based PV plants require land surface for the installation of solar panels and are therefore present in areas traditionally designated for agriculture.

By December 2010, ground-based PV installations had increased by 146% over the year before and provided 1,465.60 MW of power, which roughly corresponds to the 42% of the entire national PV potential (Frascarelli and Ciliberti 2011; GSE 2011a). According to GSE reports, land allocated for PV energy production amounts to 3,317 ha and represents about 0.026% of the total agricultural land used (GSE 2011a). Despite the relatively low percentage of land used for PV energy production, the PV industry has significant potential for growth due to the abundant availability of surfaces meeting the standards for both rooftop and ground-based installations. In addition, due to the negative trend in returns from agriculture, provision of land for PV energy production represents a crucial opportunity for the sector since it may represent a viable source of income and allow farmers to hedge against fluctuations in the commodities' price (Di Mambro 2011).

Although investments in PV power plants involve high upfront costs, the system of feed-in tariffs introduced by the Italian government supports farmers who wish to pursue this option. Apart from such direct investments, farmers are also increasingly opting to lease their land to private companies engaged in PV power generation (Bignami 2010; Sangiovanni 2010). The proposed formula is generally based on a long-term leasing agreement where a payment is made for the use of the land over the entire contract duration (Mazzanti 2010). Unlike PV installations on traditional farms, which are generally of limited scale and mostly integrated within the farm facilities, the panels in the solar farms are ground-based and cover large land surface.

In this paper, we focus on these leasing agreements[3] and set up a model where the decision to lease land is analysed under a real option approach (see Dixit and Pindyck 1994). We focus on the decision making of farmers to continue agricultural production or lease the land for PV power since it is becoming a growing phenomenon in Italy with a major impact on the regions of Puglia, Lazio and Emilia-Romagna. We assume uncertain agricultural net revenues and consider the leasing agreement as an irreversible decision (Bignami 2010). Hence, the farmer may be seen as holding an American-put option which, once exercised, entitles him to a flow of certain payments which accrue for the entire contract duration. Since, by signing the contract, the farmer loses the right to farm his land for the entire contract length then he must account for the opportunity

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[1] See for instance Parida et al. (2011) on solar energy and photovoltaic technologies. On environmental and social issues related to the use of PV energy see Andersson et al. (1998) and Focacci (2009).

[2] GSE (Gestore dei Servizi Energetici) is a publicly-owned company promoting and supporting the development of renewable energy sources (RES) in Italy.

[3] Note that however the model is general enough to also be applied to a situation where a farmer invests directly in PV energy generation.

cost of his decision, i.e. the foregone agricultural profits which could have been potentially earned keeping the land under agriculture. In our model we study the optimal timing for the farmer to exercise the option to sign a leasing agreement. This corresponds to the solution of a standard optimal stopping time problem. We solve it and determine the critical agricultural profit level at which, accounting for uncertainty in the agricultural commodities' prices and leasing payment level, leasing is preferred to agricultural production.

Our paper belongs to a vast family of contributions using option theory for the analysis of land allocation. In particular, our model is similar to ones used by Conrad (1997) and Isik and Yang (2004). In Conrad (1997), option theory is applied to determine the value of an old-growth forest stand, and the optimal harvest policy under uncertain amenity value, and known and constant stumpage value. Isik and Yang (2004) investigate the decision to enrol land in the Conservation Reserve Program (CRP). Enrolment is treated as an irreversible decision, and both agricultural net revenues and program payments are stochastic. Other interesting contributions in this literature are provided by Schatzki (2003) and Song et al. (2011). In both papers, the authors adopt the standard entry-exit model à la Dixit (1989a) to study land-use change. They allow for the possibility of switching back and forth between agricultural production and alternative land uses, including land set-aside programs and growing switchgrass for bioenergy production, respectively. In their set-up, a closed-form representation of the solution does not exist and numerical methods must be used.

Furthermore, to better illustrate our findings and provide an analysis of possible scenarios, we apply our model to the agricultural firms located in the main province of Emilia-Romagna, Bologna. In our numerical exercise we use realistic parameters to characterize the contract proposed to the farmer and estimate trend and volatility of agricultural profit dynamics using data from INEA (2011a). Results illustrate the attractiveness of the proposed leasing agreements and reveal the weakness of traditional agricultural activity as a competing alternative.

The remainder of the paper is organized as follows. In Section 2 the basic set-up for the model is presented. In Section 3 we present our case study and discuss the results of the numerical exercises. Section 4 concludes.

2 The model set-up

Consider a risk-neutral farmer contemplating the opportunity of leasing his plot for a certain period, T, to a private company. On the leased land, the company will install a power plant using a PV technology to produce and sell energy. The power plant installation and the plant maintenance costs are paid by the company. Let p denote the certain annual leasing payment to the farmer, and K the sunk cost paid by the farmer when leasing his land. This switching cost may include land clearing and/or agency cost needed to finalize the transaction between the two parties. We normalize the plot surface to 1 hectare and assume that the decision to rent is irreversible.[4] This implies that once the contract is signed, the farmer loses the possibility of managing the land surface for the entire contract length.

Due to uncertainty about output prices and yields, we assume that net returns from agriculture per hectare, π_t, fluctuates according to the following geometric Brownian motion:[5]

$$\frac{d\pi_t}{\pi_t} = \alpha dt + \sigma dz_t \tag{1}$$

where α and σ are drift and volatility, and dz_t is a standard Wiener process.

If the farmer leases his plot at the generic time t, the expected net present value of future proceeds is

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[4] Without loss of generality, due to the long contract duration, we simplify the analysis by considering the decision to lease the land as irreversible.

[5] Note that one may assume that also the contract payments follow a diversely correlated geometric Brownian motion. This possibility can be easily incorporated in our model by considering the contract payment as *numeraire* ($p = 1$) and using (1) to illustrate the stochastic fluctuations of the net return/payment ratio (see for instance Dixit, 1989b). Finally, a geometric Brownian motion with Poisson jumps can be used to model the impact of extreme and sudden shocks on π_t (see Dixit and Pindyck, 1994, pp. 85-86).

equal to:

$$\begin{aligned} NPV(\pi) &= E\{\int_0^T (p-\pi_t)e^{-rt}dt - K \mid \pi_0 = \pi\} = \int_0^T (p-\pi e^{\alpha t})e^{-rt}dt \\ &= p\frac{1-e^{-rT}}{r} - (\pi\frac{1-e^{-(r-\alpha)T}}{r-\alpha} + K) \end{aligned} \qquad (2)$$

where $r > \alpha$ is the riskless interest rate.[6]

In (2) the first term, $p\frac{1-e^{-rT}}{r}$, is the discounted flow of payments to which the farmer is entitled by contract. The second and the third term represent the cost of leasing the plot for the time period T. Such cost includes the expected value of the foregone agricultural profits, $\pi\frac{1-e^{-(r-\alpha)T}}{r-\alpha}$, plus the switching cost, K. By using a standard NPV decision rule, the farmer should sign the contract as soon as $NPV(\pi) \geq 0$. That is, as soon as

$$\pi \leq \pi^{NPV} = \frac{p\frac{1-e^{-rT}}{r} - K}{\frac{1-e^{-(r-\alpha)T}}{r-\alpha}} \qquad (3)$$

Taking a real options perspective the farmer can be viewed as holding an American put like option having the sum of foregone profits and switching cost as strike price. The exercise of such an option will be triggered by a critical time threshold, π^*, at which, accounting for uncertainty on agricultural profits and contract payment level, leasing is preferred to the agricultural activity.

Denote by $F(\pi)$ the value of the option to lease the plot. In the continuation region, $\pi^* < \pi$, the value of such an option is given by:[7]

$$F(\pi) = e^{-rt}E\left[F(\pi + d\pi)\right] \qquad (4)$$

By using Ito's lemma to expand the RHS of (4), we obtain

$$\frac{\sigma^2}{2}\pi^2 F''(\pi) + \alpha\pi F'(\pi) - rF(\pi) = 0 \qquad (5)$$

The solution to (5) takes the following functional form:[8]

$$F(\pi) = A_2\pi^{\beta_2}$$

where β_2 is the negative root of the characteristic equation $W(\beta) = \frac{1}{2}\sigma^2\beta(\beta-1) + \alpha\beta - r = 0$ and A_2 is a constant to be determined.

The value of the option and the critical exercise threshold can be determined by imposing value matching and smooth pasting conditions at π^*. That is

$$F(\pi^*) = NPV(\pi^*),\ F'(\pi^*) = NPV'(\pi^*) \qquad (5.1\text{-}5.2)$$

The system (5.1-5.2) si solved for π^* and A_2. It follows that

Proposition 1 *The critical profit level, π^*, for leasing land is :*

$$\pi^* = \frac{\beta_2}{\beta_2 - 1}\pi^{NPV} \qquad (6)$$

while the value function takes the form

$$F(\pi) = \begin{cases} NPV(\pi^*)(\frac{\pi}{\pi^*})^{\beta_2} & \text{for } \pi > \pi^* \\ NPV(\pi) & \text{for } \pi \leq \pi^* \end{cases} \qquad (6.1)$$

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[6] To incorporate a proper risk adjustment it suffices to take the expected value with respect to a distribution of π_t adjusted for risk neutrality (see Cox and Ross, 1976). Finally, note that if $r \leq \alpha$ then leasing would never be optimal for the farmer.

[7] We drop the time subscript for notational convenience.

[8] The general solution to (5) is $F(\pi) = A_1\pi^{\beta_1} + A_2\pi^{\beta_2}$ where $\beta_1 > 1$ and $\beta_2 < 0$ are the roots of $W(\beta) = 0$ and A_1 and A_2 are two constants to determined. However, since the value of the option to lease should vanish as $\pi \to \infty$ ($\lim_{\pi\to\infty} F(\pi) = 0$) then we must drop the first term by setting $A_1 = 0$.

Proof. See Appendix A.1. ■

The critical threshold, π^*, represents the optimal threshold at which the farmer shuts down agricultural production and leases the plot for PV energy production. For agricultural profits higher than π^*, the farmer should keep the option to lease, and continue agricultural production on the land. On the contrary, for $\pi \leq \pi^*$, it is more profitable to shut down and lease the plot in exchange for the flow of fixed payments, p. Note that since $\frac{\beta_2}{\beta_2 - 1} < 1$, then $\pi^* < \pi^{NPV}$. Hence, under a real option approach, the farmer postpones his decision to lease his land with respect to when it would be profitable under a NPV approach.[9]

3 Empirical application

The total agricultural land area (hereafter, TAL) in Italy amounts to 17,277,022.97 ha (ISTAT 2011). The area currently used for agricultural production, the so called used agricultural land (hereafter, UAL), is equivalent to 74.5% of TAL. The remaining land, even if available for agriculture, is currently idle. In general, ground-based PV plants and agriculture may be competing land uses (Sangiovanni 2010). However, at a national level, the land area designated for ground-based PV installations is relatively small.[10] In fact, according to GSE (2011a), this area represents approximately 0.026% of UAL and 0.076% of the agricultural land currently not being used (see Table 1).

Table 1 shows the area in hectares occupied by ground-based PV installations for every region in Italy. In addition, the table displays the regional TAL, UAL and unused agricultural land in 2010. The ratio PV area

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[9] Note that as $\sigma \to 0$ then $\frac{\beta_2}{\beta_2 - 1} \to 1$ and (6) reduces to the standard NPV decision rule.

[10] Note that the area covered by solar panels is between 6.6 to 8.2 m^2 per $\mathrm{kW_p}$. However, the area needed is usually larger since the modules must be installed with spacing in between in order to avoid mutual shading (Chiabrando et. al, 2009).

on agricultural land shows the percentage of agricultural land overtaken by ground-based PV installations.

Table 1: Ground-based PV plants and agricultural land (december 2010)

Region	PV area (ha)	TAL*	UAL**	TAL-UAL	PV area/ TAL (%)	PV area/ UAL (%)	PV area/ TAL-UAL (%)
Piemonte	134.22	1,364,088.61	1,048,350.45	315,738.16	0.0098	0.0128	0.0425
Valle d'Aosta	0.70	119,140.27	55,384.41	63,755.86	0.0006	0.0013	0.0011
Lombardia	91.83	1,228,274.57	984,870.55	243,404.02	0.0075	0.0093	0.0377
Trentino Alto Adige	7.36	897,826.17	380,502.92	517,323.25	0.0008	0.0019	0.0014
Veneto	123.00	1,021,968.76	806,319.31	215,649.45	0.0120	0.0153	0.0570
Friuli Venezia Giulia	40.88	278,596.89	219,909.72	58,687.17	0.0147	0.0186	0.0697
Liguria	1.72	97,130.21	43,033.35	54,096.86	0.0018	0.0040	0.0032
Emilia-Romagna	337.77	1,364,698.74	1,066,773.17	297,925.57	0.0248	0.0317	0.1134
North	**737.48**	**6,371,724.22**	**4,605,143.88**	**1,766,580.34**	**0.0116**	**0.0160**	**0.0417**
Toscana	75.77	1,377,113.60	755,295.11	621,818.49	0.0055	0.0100	0.0122
Umbria	44.19	537,144.00	327,868.41	209,275.59	0.0082	0.0135	0.0211
Marche	179.39	632,230.85	473,063.85	159,167.00	0.0284	0.0379	0.1127
Lazio	386.82	925,046.28	648,472.52	276,573.76	0.0418	0.0597	0.1399
Center	**686.17**	**3,471,534.73**	**2,204,699.89**	**1,266,834.84**	**0.0198**	**0.0311**	**0.0311**
Abruzzo	34.44	684,047.90	449,988.65	234,059.25	0.0050	0.0077	0.0147
Molise	18.11	254,360.83	196,527.69	57,833.14	0.0071	0.0092	0.0313
Campania	34.64	723,215.48	547,464.53	175,750.95	0.0048	0.0063	0.0197
Puglia	1,483.95	1,395,655.14	1,280,875.86	114,779.28	0.1063	0.1159	1.2929
Basilicata	72.82	654,957.90	512,280.88	142,677.02	0.0111	0.0142	0.0510
Calabria	30.68	707,215.08	551,404.94	155,810.14	0.0043	0.0056	0.0197
South	**1674.64**	**4,419,452.33**	**3,538,542.55**	**880,909.78**	**0.0379**	**0.0473**	**0.1901**
Sicilia	180.27	1,545,976.98	1,384,043.04	161,933.94	0.0117	0.0130	0.1113
Sardegna	38.38	1,468,334.71	1,152,756.54	315,578.17	0.0026	0.0033	0.0122
Islands	**218.65**	**3,014,311.69**	**2,536,799.58**	**477,512.11**	**0.0073**	**0.0086**	**0.0458**
Total	**3,316.94**	**17,277,022.97**	**12,885,185.90**	**4,391,837.07**	**0.0192**	**0.0257**	**0.0755**

*Total agricultural land, **Used Agricultural Land

The region of Emilia-Romagna is located in the north of Italy and is among the regions with higher agricultural productivity. Emilia-Romagna is particularly known for the production of cereals, potatoes, maize, tomatoes and onions. Important quantities of fruit and wine grapes are also produced in this region (Boccaletti et al. 2011). In 2010, the regional UAL was equal to 1,066,773 ha, which represents 8.3% of the country's UAL. Arable land accounted for 78% of the regional UAL while the remaining used land is allocated to tree crops (12.13%), meadows and pasture (9.74%), and family gardens (0.13%) (INEA 2011b).

At the end of 2010,[11] ground-based installations covered 337.77 ha of land in the region producing a total of 157.5 MW (GSE 2011a). This represents 43.26% of the total PV power produced in Emilia-Romagna in 2010, which equals 363.9 MW. Table 1 also shows that the area of agricultural land being overtaken by ground-based PV installations is not high. It covers approximately 0.025% of UAL and 0.11% of the land not used in the region of Emilia-Romagna.

In the following, our analysis focuses on Bologna, which is the main province of Emilia-Romagna and the leading province with respect to the number of installations. It currently has 2,683 PV power plants which provide 66.1 MW of production capacity[12] (GSE 2011a). The province of Bologna also has the largest area of agricultural land in the region and the highest net revenues from agricultural production (INEA 2011a). Our study is based on data pertaining to arable lands in plain and hilly landscapes. The choice of arable lands was made since they account for the majority of crops grown in the province. Both plain and hilly landscapes

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[11] However, as said in the introduction, due to the rapid rate of expansion in PV industry, the PV plants currently active are 25,633 for a power generating potential of 1,080.3 MW. This figure was provided by ATLAS, an online service available on the GSE's website (see http://atlasole.gse.it/atlasole/).

[12] However, in terms of power production potential, the province of Ravenna is much above Bologna with a total capacity of 128.3 MW.

were investigated as agricultural net revenues vary accordingly. Since PV power plants are mostly installed in plain landscapes, we focus on this land type and present the case of hilly landscapes in appendices. In the next section we provide an analysis of several possible scenarios based on parameter estimates taken from data on agricultural net revenues, current values for lease payments, the initial switching cost and the discount rate.

3.1 Agricultural net revenues: parameter estimates

In order to construct a time series of the agricultural net revenues for the province of Bologna we use the yearly arable land values provided by INEA (Istituto Nazionale di Economia Agraria). These values account for the average regional price indexes aggregated by geographical area and type of crop (INEA 2011a). As in Edwards (2011) we compute the agricultural net revenues by assuming a 5% rate of return[13] on the land value (see figure[14] 1).

By Ito's Lemma, if π_t fluctuates according to (1) then its natural logarithm, $\ln(\pi_t)$, follows an arithmetic Brownian motion with drift. That is:

$$d\ln(\pi_t) = \mu dt + \sigma dz_t \tag{7}$$

where $\mu = \alpha - \frac{\sigma^2}{2}$.

In order to test whether the empirical data on net revenues satisfy equation (7), let approximate $d\ln(\pi_t)$ as follows:

$$\Delta\ln(\pi_t) = \ln(\pi_t) - \ln(\pi_{t-1}) = \mu\Delta t + \varepsilon_t\sqrt{\Delta t} \tag{8}$$

where $\varepsilon_t \sim N(0,1)$. To have the time series on net revenues consistent with equation (7) then the series $\Delta\ln(\pi_t)$ must follow a random walk and be non-stationary (Gujarati 2004). We proceed by rearranging (8) as follows

$$\Delta\ln(\pi_t) = \delta_0 + \delta_1\ln(\pi_{t-1}) + \sum\nolimits_{i=2}^{q}\delta_i\Delta\ln(\pi_{t+1-i}) + e_t, \tag{9}$$

where $\delta_0 = \mu\Delta t$ and $e_t = \sigma\varepsilon_t\sqrt{\Delta t}$, and taking an augmented Dickey-Fuller (ADF) test to check the non-stationarity of the time series (see Table 4 in A.3). Hence, we can use the t-statistic to test the null hypothesis of unit root, i.e $H_0 : \delta_0 = 0$. In the appendices, we show that the t-values are higher than the critical values set for 1%, 5% and 10% significant levels for both the time series, i.e. plain and hilly landscapes. This implies that the null hypothesis is not rejected. Finally, it follows that the maximum-likelihood estimates for α and σ are given by:

$$\alpha = \mu_l + \frac{\sigma_l^2}{2},\ \sigma = \sigma_l \tag{10}$$

where μ_l and σ_l are mean and standard deviation of the series $\Delta\ln(\pi_t)$. That is, $\alpha \simeq 0.02$ and $\sigma \simeq 0.06$, respectively representing drift and volatility for agricultural net revenues in plain landscapes. In the case of

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[13] This is the rate of return paid on the Italian multi-year treasury bonds, BTP (Borsa Italiana, 2011). See also Focacci (2009).

[14] The relative time series is available in Appendix A3. See Table 4.

hilly landscapes, we obtain $\alpha \simeq 0.035$ and $\sigma \simeq 0.051$ (see Appendix A.3).

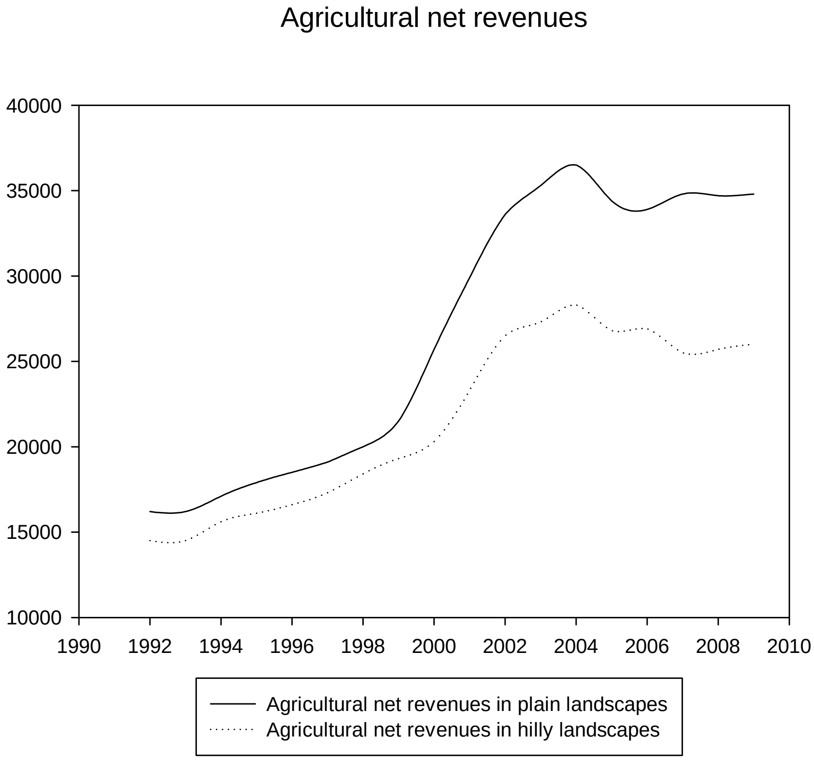

Figure 1: Agricultural net revenues in plain and hilly landscapes 1992-2009 (€1992/ha)

In Emilia-Romagna the yearly payment per hectare offered to landowners situated in plain landscapes to lease their plot for the installation of a PV plant varies from € 2,000 to € 4,000 (Bignami 2010). Its level is certain and subject to inflation correction. The payment level depends on land characteristics and type of crop cultivated. The contract duration is usually equal to 20 years since this corresponds to the time period where the PV plant may qualify for the benefits paid on the basis of *Conto Energia*.

Finally, some transaction costs including land clearing and agency costs must be considered. In our paper, we abstract from land clearing costs and consider only transaction costs by assuming that they represent a percentage k of the first contract payment.

3.2 Critical threshold and sensitivity analysis

In this section we discuss only the case of arable land in plain landscapes.[15] For our base case, represented in bold in our tables, we set the drift equal to 2% and volatility of 6% obtained by the time series. In addition, the discount rate is set equal to 5%. Furthermore, the leasing payment is considered to be equal to € 3000, which represents the average payment per hectare offered in the region. The switching cost k is set equal to 50% of the initial leasing payment. Then, to illustrate the effect of each parameter on the critical threshold we provide a sensitivity analysis. The critical threshold, representing the value at which it is beneficial for the farmer to lease the land, is obtained by equation (6). In Table 2 we show the variation of the critical

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[15] The relative numerical exercise and sensitivity analysis for hilly landscapes is available in section A.4 of the appendices.

thresholds due to a change in drift, volatility and discount rate.

Table 2: Critical threshold and sensitivity analysis on α, σ and r

r	0.05			0.07		
σ	0.06	0.10	0.20	0.06	0.10	0.20
$\alpha = 0.02$	**2,240.20**	2,017.77	1,483.39	2,261.85	2,061.77	1,586.60
$\alpha = 0.04$	1,924.14	1,791.54	1,373.29	1,961.82	1,834.45	1,451.46
$\alpha = 0.06$	-	-	-	1,649.41	1,569.36	1,286.38
$T = 20$ years, $k = 50\%$, and $p = 3{,}000.00$						

In our base scenario, the critical threshold is equal to € 2,240.20. This critical threshold must be compared to current pay-offs from agricultural production which equal € 1,740 per hectare in plain landscapes (INEA 2011a). Thus, it is profitable for the farmer to exercise the option to lease his plot. For the same level of volatility, an increase in the drift induces a decrease in the critical threshold. This in turn implies that the landowner postpones the decision to lease in expected terms. Note that when the drift is equal to 6%, higher than the discount rate set at 5%, leasing the plot would never be optimal for the farmer. Similarly, as volatility rises, the critical threshold increases. With respect to its base level, we note that it is still beneficial to lease the plot for some higher volatility levels. However, for σ set at 20%, it is no longer profitable and the landowner continues farming the plot and keeps open the option to lease.

An increase in the discount rate has a positive impact on the timing of the option to lease. In fact, as the interest rate increases, the critical threshold becomes € 2,261.85. Hence, the landowner exercises the option to lease earlier, and for higher agricultural net revenue values.

In Table 3 we show how a change in the contract duration, leasing payment, and initial switching cost can affect the critical threshold. We keep the drift, volatility and interest rate as set for the base case.

Table 3: Critical threshold and sensitivity analysis on k, p, and T

k	50%			100%		
p	2,000.00	3,000.00	4,000.00	2,000.00	3,000.00	4,000.00
$T = 20$	1,493.46	**2,240.20**	2,986.93	1,431.97	2,147.95	2,863.93
$T = 25$	1,448.05	2,172.08	2,896.10	1,395.47	2,093.20	2,790.94
$T = 30$	1,405.82	2,108.73	2,811.63	1,359.07	2,038.61	2,718.15
$\alpha = 0.02$, $\sigma = 0.06$, and $r = 0.05$						

Table 3 illustrates that when the leasing payment is set at € 2,000 and the switching costs are equal to 50% of the initial payment, leasing the plot is not beneficial for the farmer since the current agricultural net revenues level is above the critical threshold. A rise in the yearly leasing payment induces an increase in the critical threshold, and the farmer exercises the option to lease earlier. By considering an increase in the leasing payment from € 2,000 to € 3,000 and a 20 year contract duration, the critical threshold increases from € 1,493.46 to € 2,240.20. As a result of an increase in the contract duration, the critical threshold decreases. Table 3 shows that when the leasing payment is set at € 3,000, the critical threshold is equal to € 2,240.20 for a lease agreement lasting 20 years. It however decreases to € 2,172.08 when the leasing contract considered is set at 25 years. Therefore with a longer contract duration the landowner postpones the decision to lease. This decrease follows immediately as a consequence of the value attached to the flexibility which is implicitly given up by leasing.

Additionally, Table 3 illustrates that if the switching cost increases from 50 to 100% of the leasing payment, the critical threshold decreases. If the switching cost is high, the landowner exercises the option to lease later and for lower agricultural net revenue values.

The model, presented in section 2, allows for the calculation of the minimum leasing payment, $\underline{p}$, triggering the acceptance of a leasing agreement. This is done by rearranging (6) and letting p be a function of the current agricultural net revenues. It follows that:

$$\underline{p} = \frac{(1-\frac{1}{\beta_2})\frac{1-e^{-(r-\alpha)T}}{r-\alpha}\pi + K}{\frac{1-e^{-rT}}{r}} \tag{11}$$

Considering a drift of 2% and volatility of 6% obtained by the time series representing the agricultural net revenues and setting the discount rate equal to 5%, the minimum leasing payment for which it is more beneficial for the landowner to lease the plot is € 2,356.64. This leasing payment is within the range of payments offered in the region that varies from € 2,000 to € 4,000.

4 Conclusions

The main aim of this paper was to determine the factors affecting the decision of a risk-neutral farmer to quit agricultural production and lease the land to a firm investing in a PV power plant.

A simplified model was developed and applied to the agricultural firms situated in the province of Bologna (Italy). We assume that the leasing payment offered to the farmer is known and certain, while the agricultural net revenues follow a geometric Brownian motion. The data obtained from the INEA database were consistent with our assumption, and were characterized by a drift equal to 2% and volatility of 6% for plain landscapes. We show that it is more profitable for agricultural firms situated in the province of Bologna to exercise the option to lease if the pay-offs from agricultural production are lower than or equal to € 2,240.20 per hectare. Since the current agricultural net revenues in plain landscapes equal € 1,740.00 per hectare,[16] then it is more profitable for the agricultural firms to stop farming and lease the land to a company investing in PV power generation. In addition, we show that the decision to lease is postponed with respect to the timing resulting from the application of the net present value (NPV) rule. This is a standard result in the real option literature since under uncertainty it is recommended to postpone the exercise of the option. The comparative statics performed to study the impact of different parameters on the optimal leasing time are in line with the literature.[17] As uncertainty about the agricultural net revenues and/or expected profit growth rate soar, the leasing agreement is postponed in expected terms. Similarly, the longer the contract duration, the lower the critical profit level triggering the leasing agreement. This is a straightforward consequence of the value attached to the flexibility that is implicitly given up by signing the contract. This effect may be balanced by paying a higher lease amount to the landowner. Finally, as expected, an increasing interest rate induces an earlier exercise.

The decrease in incomes from agricultural production on one hand (Di Mambro 2011) and the feed-in tariffs, keeping high the level of leasing payment offered, on the other, have induced an increasing rate of agricultural land overtake for the production of PV energy. This dynamic may lead to a conflict between energy and food for the allocation of land.[18] In this respect, as stated by Nonhebel (2005), PV energy provision requires less land area than that needed in the growth of energy crops. Our results also confirm that at least currently only a limited land area is used for ground-based PV installations. This area corresponds to only 0.025% of the used agricultural land in the region of Emilia-Romagna (GSE 2011a). In addition, 21.83% of the total regional agricultural land is currently unused and could be employed in the production of PV energy.

By bringing this discussion to a national level, the land which is classified as agricultural and not used amounts to 4,391,837.07 ha while the area covered by PV plants is equal to 3,316.95 ha. According to this data, even if the land used for ground-based PV power plants comes only from unused agricultural areas, there is still available land for the production of approximately 1.9 TW of electric power. To conclude, potential conflict for land allocation can be avoided by designing energy policies that prioritise unused agricultural areas for the production of renewable energy.

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[16] Appendix A4 shows that the results follow the same trend in hilly landscapes. The critical threshold is equal to € 1.517,31, higher than the current agricultural net revenues equal to € 1.300.

[17] Note that, apart from the derivatives with respect to sunk switching cost, rent payment level and uncertainty, the effect of other parameters is in general, as shown in the appendix, non-monotone. However, as illustrated in section 3, the discussion provided in the introduction holds when realistic parameters are considered.

[18] See Chakravorty et al. (2009) for a discussion of the trade-off between energy and food crops.

A Appendix

A.1 Proof of proposition 1

By plugging $F(\pi) = A_2\pi^{\beta_2}$ into (5.1-5.2) we obtain

$$A_2\pi^{*\beta_2} = NPV(\pi^*),\ A_2\beta_2\pi^{*\beta_2-1} = -\frac{1-e^{-(r-\alpha)T}}{r-\alpha} \tag{A.1.1-A.1.2}$$

Solving for π^* and A_2 yields (6) and (6.1).

A.2 Comparative statics

The derivative with respect to K, p and σ^2 are straightforward:

$$\begin{aligned}\frac{\partial\pi^*}{\partial K} &= -\frac{\beta_2}{\beta_2-1}\frac{K}{\frac{1-e^{-(r-\alpha)T}}{r-\alpha}} < 0,\\ \frac{\partial\pi^*}{\partial p} &= \frac{\beta_2}{\beta_2-1}\frac{\frac{1-e^{-rT}}{r}}{\frac{1-e^{-(r-\alpha)T}}{r-\alpha}} > 0,\\ \frac{\partial\pi^*}{\partial\sigma^2} &= -\frac{\partial\beta_2}{\partial\sigma^2}\frac{\pi^{NPV}}{(\beta_2-1)^2} < 0\end{aligned} \tag{A.2.1-A.2.3}$$

where $\frac{\partial\beta_2}{\partial\sigma^2} = -\frac{\frac{1}{2}\beta_2(\beta_2-1)}{\sigma^2\beta_2-(\frac{1}{2}\sigma^2-\alpha)} > 0$.

On the contrary, derivatives for T, α and r may change sign over the set where those parameters are defined. Differentiating with respect to T we obtain:

$$\frac{\partial\pi^*}{\partial T} = \frac{\beta_2}{\beta_2-1}\frac{\partial\pi^{NPV}}{\partial T} \tag{A.2.4}$$

where $\frac{\partial\pi^{NPV}}{\partial T} = \frac{pe^{-\alpha T}-\pi^{NPV}}{(\frac{1-e^{-(r-\alpha)T}}{r-\alpha})}e^{-(r-\alpha)T}$. It follows that:

$$\frac{\partial\pi^{NPV}}{\partial T} = \begin{cases} \leq 0 & \text{for } pe^{-\alpha T} \leq \pi^{NPV} \\ > 0 & \text{otherwise} \end{cases} \tag{A.2.4a}$$

Now, let rearrange π^* as follows:

$$\pi^* = (\frac{1}{2}\sigma^2\beta_2 + r)\frac{p\frac{1-e^{-rT}}{r} - K}{1-e^{-(r-\alpha)T}} \tag{A.2.5}$$

Differentiating (A.2.5) with respect to α we obtain:

$$\frac{\partial\pi^*}{\partial\alpha} = \frac{1}{2}\sigma^2\frac{\partial\beta_2}{\partial\alpha}\frac{\pi^{NPV}}{r-\alpha} + (\frac{1}{2}\sigma^2\beta_2 + r)\frac{\pi^{NPV}}{r-\alpha}\frac{Te^{-(r-\alpha)T}}{1-e^{-(r-\alpha)T}} \tag{A.2.6}$$

where $\frac{\partial\beta_2}{\partial\alpha} = -\frac{\beta_2}{\sigma^2\beta_2-(\frac{1}{2}\sigma^2-\alpha)} < 0$. Rearranging (A.2.6) yields:

$$\frac{\partial\pi^*}{\partial\alpha} = \begin{cases} \leq 0 & \text{for } T \leq \widetilde{T} \\ > 0 & \text{otherwise} \end{cases} \tag{A.2.7}$$

where $\widetilde{T} = \frac{\partial\beta_2}{\partial\alpha}\frac{1-e^{(r-\alpha)T}}{\beta_2+2\frac{r}{\sigma^2}} > 0$.

Finally, the derivative of π^* with respect to r is given by:

$$\frac{\partial\pi^*}{\partial r} = \frac{-\frac{\partial\beta_2}{\partial r}\pi^{NPV} + \frac{\partial\pi^{NPV}}{\partial r}\beta_2(\beta_2-1)}{(\beta_2-1)^2} \tag{A.2.8}$$

where $\frac{\partial\beta_2}{\partial r} = \frac{1}{\sigma^2\beta_2-(\frac{1}{2}\sigma^2-\alpha)} < 0$. It follows that:

$$\frac{\partial\pi^*}{\partial r} = \begin{cases} \leq 0 & \text{for } \frac{\frac{\partial\pi^{NPV}}{\partial r}}{\pi^{NPV}} \leq S \\ > 0 & \text{otherwise} \end{cases} \tag{A.2.9}$$

where $S = \frac{\frac{\partial\beta_2}{\partial r}}{\beta_2(\beta_2-1)}$.

A.3 Agricultural net revenues and unit root test

Table 4 shows the net revenues from agricultural production in plain and hilly landscapes in the province of Bologna. Only arable lands are taken into consideration and the values are adjusted to 1992 levels. The statistical tests show that the time series are not stationary and, as a result, drift and volatility can be obtained as shown below.

Table 4: Agricultural net revenues and unit root test

Year	**Net revenues in plain landscapes**	**Net revenues in hilly landscapes**
1992	769.23	688.51
1993	735.40	658.23
1994	745.68	680.27
1995	741.99	667.37
1996	738.07	662.27
1997	747.07	676.67
1998	766.93	705.58
1999	810.67	727.72
2000	945.40	746.76
2001	1,069.94	833.77
2002	1,173.02	925.15
2003	1,199.97	928.02
2004	1,214.05	941.31
2005	1,121.77	873.93
2006	1,082.73	859.15
2007	1,092.89	800.83
2008	1,054.94	781.32
2009	1,049.58	784.17
μ	**0.018**	**0.034**
σ	**0.060**	**0.051**
α	**0.020**	**0.035**

Unit root test

Time series in plain landscapes

		t-Statistic	Prob.
Augmented Dickey-Fuller test statistic		-1.929402	0.3117
R-squared	0.553909	Mean dependent var	19.63617
Adjusted R-squared	0.485279	S.D. dependent var	59.54229
S.E. of regression	42.71804	Akaike info criterion	10.51448
Sum squared resid	23,722.80	Schwarz criterion	10.65934
Log likelihood	-81.11584	Hannan-Quinn criter.	10.52190
F-statistic	8.071013	Durbin-Watson stat	2.062485
Prob(F-statistic)	0.005263		

Time series in hilly landscapes

		t-Statistic	Prob.
Augmented Dickey-Fuller test statistic		-1.757859	0.3859
R-squared	0.345865	Mean dependent var	7.871207
Adjusted R-squared	0.245229	S.D. dependent var	41.82275
S.E. of regression	36.33459	Akaike info criterion	10.19078
Sum squared resid	1,7162.63	Schwarz criterion	10.33564
Log likelihood	-78.52623	Hannan-Quinn criter.	10.19820
F-statistic	3.436785	Durbin-Watson stat	2.291900
Prob(F-statistic)	0.063363		

ADF test critical values

1% level	-3.92035
5% level	-3.065585
10% level	-2.673459

A.4 Critical thresholds and minimal leasing payment in hill landscape

The time series representing the agricultural net revenues in hilly landscapes is characterized by $\alpha = 0.035$ and $\sigma = 0.051$.The sensitivity analysis on π^* as a result of a change in the α, σ, and r is illustrated in Table 5. The base case is shown in bold. Considering the current net revenues per hectare from agricultural production, equal to € 1,300.00, it is more profitable for farmers to exercise the option to lease since the critical $\pi^* = 1,517.31$.

Table 5: Critical threshold and sensitivity analysis on α, σ and r

r	0.05			0.07		
σ	0.051	0.10	0.20	0.051	0.10	0.20
$\alpha = 0.02$	1,714.46	1,513.80	1,112.78	1,728.16	1,546.85	1,190.28
$\alpha = 0.035$	**1,517.31**	1,385.94	1,051.13	1,542.24	1,416.99	1,112.95
$\alpha = 0.06$	-	-	-	1,247.13	1,177.02	964.78
T = 20 years, k = 50%, and p = 2,250.00						

Table 6 shows the sensitivity analysis on π^* as a result of a change in the k, p and T.

Table 6: Critical threshold and sensitivity analysis on k, p, and T

k	50%			100%		
p	1,500.00	2,250.00	3,000.00	1,500.00	2,250.00	3,000.00
$T = 20$	1,011.54	**1,517.31**	2,023.08	969.89	1,454.83	1,939.78
$T = 25$	949.40	1,424.11	1,898.81	914.93	1,372.40	1,829.86
$T = 30$	893.47	1,340.20	1,786.93	863.76	1,295.64	1,727.52
α = 0.035, σ = 0.051%, and r = 0.05						

Using equation (11), the minimum lease payment for which it is profitable for landowners situated in hilly landscapes to lease the land is equal to € 1,940,50.

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